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ATMOSPHERIC COMPENSATION APPLICATIONS AND DATA

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This technical report has been reviewed and is approved for publication.

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Activity on this contract is divided between validation and verification testing of FLAASH and its radiative transport engine "MODTRAN", and data collection planning and analysis needed to calibrate and validate flight hyperspectral instruments. Major efforts included the atmospheric compensation code "Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes: (FLAASH), the MightySat II.1 Hyperspectral Interferometer (referred to herein as MS II.1), the Warfighter-1 Hyperspectral Imager (referred to herein as WF-1), the Noble EYE hyperspectral program, and the COMPASS hyperspectral program.

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1. INTRODUCTION

Activity on this contract is divided between validation and verification testing of FLAASH and its Radiative transport engine "MODTRAN", *and* data collection planning and analysis needed to calibrate and validate flight hyperspectral instruments. Major efforts included the atmospheric compensation code "Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes" (FLAASH), the MightySat II.1 Hyperspectral Interferometer (referred to herein as MS II.1), the Warfighter-1 Hyperspectral Imager (referred to herein as WF-1), the Noble EYE hyperspectral program, and the COMPASS hyperspectral program.

2. MAJOR EFFORTS

2.1 MightySat II.1 Hyperspectral Interferometer

The MS II.1 sensor was launched in July, 2000. For this sensor, we supported pre-flight efforts to establish a data processing hierarchy and data flow chain and post-launch efforts to process the sensor data into a meaningful product. The sensor produces hypercubes whose dimensions are interferometric reading by cross-track distance by along-track flight distance. Desired products are geo-rectified hyperspectral cubes with dimensions of latitude, longitude, and spectrally-resolved radiance. Because the sensor was never properly calibrated pre-flight, several flaws in the data needed to be rectified to correctly process the interferograms into calibrated spectral hypercubes. The instrument served its initial purpose well, namely to demonstrate the possibility of using inexpensive components on orbit. The secondary purpose for MS II.1, acquisition of scientifically useful hyperspectral data, was not successful because the "Fourier Transform Hyperspectral Imager" instrument design, construction, and calibration efforts were under-funded and under-performed by the instrument provider.

A major portion of our MS II.1 effort was to determine the correct coefficients to account for "cold pixels" on the detector. A cold pixel is one that produces a smaller-than-group-average value (in counts) for a uniform illumination on a group of pixels. Because the MS II.1 sensor records interferograms, the lower-level spike in a single pixel can have a dramatic impact on the processed spectral results (a spike of this sort on an interferogram can produce a sine wave interfering with the actual spectral result). The sensor was constructed by Kestrel Corporation for the Air Force under an SBIR contract. The amount of time allotted to instrument calibration in their construction and testing program has been reported by Kestrel as less than one day. The detector CCD chip has dozens of possible acquisition modes based on percentage of the detector in use, accumulation time, detector pixel binning in either or both dimensions on the detector chip, and electronic offset. As a result, the calibration day had only one test mode that closely matched the final chosen flight-default acquisition mode (differing only by a factor of two in accumulation time). This test consisted of 25 image frames with the sensor illuminated by a labsphere, followed by 25 dark image frames, all at a frame rate of 30 frames per second. Thus, the pre-flight calibration data provided to our group on which to base a pre-flight calibration consisted of 1.67 seconds of actual instrument data acquisition time. Although this is clearly inadequate to calibrate an instrument, the pre-flight data did contain enough information to calculate a cold pixel map for the flight data.

The cold pixel map (CPM) was produced by visual inspection of each interferogram (IFG) in the half of the detector used in default flight configuration. Low-signal pixels were compared with matching-position pixels in other IFGs, using the centerburst drift along the chip to determine matching IFGs. The IFG average level was also taken into account, as the sensor throughput did not provide a uniform flux at each IFG. The resulting CPM eliminated at least 99 percent of the noise spikes in flight data, and became a routine data processing step.

The MS II.1 sensor receives light through a telescope and entrance slit. The image of the slit is split in a Sagnac interferometer to produce two slit images that are combined to form interference patterns. The interference patterns are projected onto, and recorded by, a CCD two-dimensional array detector. The optical path in the MS II.1 instrument was severely flawed. In addition to the intended signal (i.e. the interferometric patterns), the CCD was being struck directly by broadband light, referred to as "glint," that appears to be light passing through the instrument entrance slit at a relatively large off-normal angle. The light may have been entering the instrument through a path that does not include the entrance slit; however, the shape of the glint is consistent with the source having the shape of the slit. Although there was a general pattern to the glint, the absolute brightness and the along-chip shape of the glint are both variable and therefore cannot be calibrated out of the signal directly. Instead, computational massaging was required for the individual IFGs to reject the broadband contaminant.

In addition to previously reported sensor flaws, a ghost (a doubled-image) was also apparent in the MS II.1 data. Because this sensor records IFGs, an entire IFG line would need to be reaching the detector in more than one location to yield the ghosts. This can occur if the entire

IFG is somehow split or multiply reflected to reach the detector in more than one location, or if the pre-IFG optical signal is split or multiply reflected to produce a ghosting in the signals that are then converted to IFGs. The use of a bare (uncoated, non-windowed) silicon detector with approximately 30 percent reflectivity is the basic design flaw leading to the multiple reflections that create the ghost image.

We recommended two particular data acquisitions, the first was to address the ghosting issue. This involved targeting the Earth's moon to provide good calibration data. Although the MightySat II.1 program team had previously attempted to target the moon, their plan for scanning was incomplete and insufficient to return the full value of this collection opportunity. In fact, the moon was briefly acquired on a small fraction of the detector. We recommended an acquisition during which the satellite is maneuvered to allow the image of the moon to be scanned slowly along the entire spatial dimension of the instrument. In addition to providing radiometric calibration data for the entire detector, this type of scan would provide an opportunity to directly measure the optical ghost that is currently damaging data from most of the detector. A view of the moon (which under fills the slit spatially) would show the ghosting component at the edge of the illuminated section. With a slow spatial scan, the ghost component could be mapped out along the slit, providing primary calibration data to accurately remove the ghost component from the routine data acquired by the instrument.

The second recommendation was to focus on littoral zones. There was a possibility that the MS II.1 data may have be able to provide relative depths in shallow areas, such as harbors. In addition to the depth study, harbors provide the opportunity to observe high-contrast reflectivity regions, specifically man-made structures (high reflectivity) against a low-reflectivity surface (water). We requested images of Boston Harbor, chosen because it is a well-documented seaport at which observations of variable large structures can be made (such as large transient ships, including oil tankers and cargo vessels). Although the images were collected, the ghost and internal glint issues precluded valid spectra.

2.2 Warfighter-1 Hyperspectral Imager

For the Warfighter-1 hyperspectral imager, we supported the construction and calibration test phase. We supported calibration efforts by reviewing test plans, recommending changes to the plans, and reviewing test data sets as they become available. Major efforts included:

(1) Analysis of spectral response data that showed the need for installation of a better grating, dramatically improving the blue response of the instrument.

(2) Evaluation of the test plan to prioritize calibration tests at a time when the available time for testing had become critical and certain tests were being reduced.

(3) Verification of detector quality from early test data.

(4) Participation in working groups to (a) correct errors in another contractor's Warfighter software design that would have yielded mis-calibrated (and wrong) radiance values; (b) select the most efficient test scheme for calibrating the individual detector spectral response functions; and (c) guide the order of calibration testing for best use of limited time in schedule.

(5) Assessment of cross talk between detector pixels.

During the construction and calibration test phase, we supported calibration efforts by direct participation in the planning and analysis of primary calibration data. Much of this work was conducted on-site at Northrop Grumman in Baltimore, MD. Extensive travel was required to support this effort.

The main test intended for our participation was the Spectral Response Function (SRF), in which a sufficient number of detector pixels were evaluated in order to characterize the optical wavelengths striking each pixel. In the course of Northrop Grumman's performance of this test, a spurious signal was found which we identified as being cross talk from particular detector elements to a series of other detector elements. Discussions with Northrop Grumman, Rockwell, and Jet Propulsion Lab teams resulted in sufficient understanding for us to specify a method to calibrate out this spurious signal. Data sets collected by Northrop Grumman formed the basis of the "cross talk removal calibration." Because the cross talk signal ranged from 1 to 10 percent of the intended signal for different detector arrays in the system, the correct cross talk removal was critically important to the successful calibration of this sensor.

Our efforts also included planning for work needed to replace inadequate data flow software that another contractor provided to the WF-1 program. Although the software as delivered met the specifications set for it initially, the actual behavior of the instrument was not considered in the software's treatment of the data. There was a significant mismatch between the early-planning hope for machine performance and the actual performance of the instrument as built, requiring replacement of the earlier software.

During the spacecraft integration phase, we supported calibration efforts by direct participation in the planning and analysis of primary calibration data. Our analysis of test data provided by Orbital Sciences, Inc., showed that the image of the slit had moved relative to the detector Focal Plane Arrays (FPA). This motion was the result of a physical motion of one or more components in the optical path inside the Warfighter-1 spectrometer. By comparing known FPA features (hot and cold pixels) we first determined that the apparent motion was actually a motion of the slit image, rather than being an error in the readout of the 3 FPAs. We also quantified the image shift and tracked it over the course of the satellite test program involving Thermal Vacuum tests. Methods were developed to monitor and quantify this shift using the on-orbit data, as the possibility existed that the image motion will recur during or after launch. In May 2001, we attended the Warfighter-1 Joint IPT planning meeting and the Orbital Sciences "Consent to Ship Review."

On 21 September 2001, a failure in the launch vehicle resulted in the destruction of Warfighter-1, after completion of approximately 1.3 orbits. We immediately began efforts to recover the lost orbital hyperspectral capability. The following is our direct analysis of the situation and assessment of possible options, initially submitted to the WF-1 Principal Investigator on 22 September 2001. That report served as the starting point for the Warfighter-2 team, which became the Noble EYE team.

<following quote from 010922-FollowOnPossibilities-JAG.doc>

22 September 2001

Follow-on Possibilities following Friday's failed launch of WF-1:

Sindri:

1) Test the idea of averaging many bands, admitting that Sindri is at best a multi-spectral instrument, evaluate usefulness as an MSI, consider keeping alive.
2) Continued operations would require the RSC to perform on-demand, 24/7, with commanding and data retrieval given top priority.
3) Stepped-up operations would be greatly improved by adding more downlink sites, to boost throughput to multiple cubes per day and to improve time-relevance.

4) Advantages: *if* Sindri functions well enough to use as a multi-spectral instrument, then the tasking side is up to speed, as is the data flow side; also, the asset is ready to use.
5) Disadvantage: MSI not as useful in general as HSI; need to get re-processing up to speed (most critical question is "how many final bands?"); Sindri would continue to have a quite limited spectral range; and usefulness of atmospheric compensation is in doubt in MSI mode (unless the 820 band could be used in HSI mode to generate the atmospheric retrieval, which could itself be degraded to MSI bands).

Hyperion:

1) If Hyperion is near the end of NASA's planned lifetime, then consider acquiring this satellite for continued operations.
2) Advantages: their "sharpened" images show detail at better than the intended 30 m GSD; they cover the full spectral range (~ 0.5 – 2.5 microns); and it *is* a grating spectrometer.
3) Disadvantages: We are not geared up to receive and process their data (this could be changed rapidly); also, NASA may have a technical reason for the short on-orbit planned lifetime. For example, is the NIR/SWIR focal plane about to run out of coolant? We'll need to understand what limitation led to their short plan.

Warfighter-2:

Can WF-2 be fabricated and integrated with OV-3 on an emergency "get it done" schedule? Design is in hand, some of the critical optics exist (at least the grating), and with the current atmosphere a high-priority project *could* conceivably be done on a drop-everything-and-make-this-happen timescale. Rockwell has claimed to have redesigned the ROIC to eliminate the cross talk problem, so WF-2 would already be an improvement over WF-1. Testing procedures at NGC are well-understood, and could potentially be stream-lined to a "get it done" schedule as well. Finally, the processing flow problems are being resolved and even the MDA software could be fixed (or replaced fully) if given sufficient priority.

Advantages: team is at full speed, this allows us to apply the built-up expertise; design is well understood, and it is a good one; OV-3 already has its telescope, and could in principle be retrofitted to include WF-2 faster than building WF-2 from scratch including a telescope and the satellite components (structure, power, communications, and control systems).

Disadvantages: even an accelerated time schedule will take quite a bit of time before WF-2 would be an asset; a get-it-done schedule would be relatively expensive; in the end, the bird would still need to be launched.

<end quote>

Following the launch loss of WF-1, we continued to assess hyperspectral capabilities and software performance using available data sets. The EO-1 "Hyperion" sensor is an on-orbit hyperspectral sensor that covers the spectral range of approximately 400 nm (blue end of visible) to 2.5 microns (short-wave infrared), roughly the same coverage range that WF-1 was built to measure. Although EO-1 ground sample distance (GSD) is 30 meters instead of the WF-1 8 m GSD, the data from EO-1 could be used to meet some of the test objectives of the WF-1 program. Some of the broader area terrain categorization goals, for example, could be tested even with the lower spatial resolution. We supported efforts to evaluate the EO-1 actual performance and develop plans to map and acquire data scenes that would allow evaluation of the WF-1 science goals. These efforts include attendance at the NASA EO-1 Calibration Validation Workshop held 23 April 2002 in Greenbelt, MD.

2.3 Noble EYE Hyperspectral Program

The Noble EYE program was organized to advance the Air Force leadership in space-based hyperspectral imagery, and we contributed to the early planning for this program. We contributed heavily to the Air Force "Request For Information" (RFI) that detailed the broad-strokes plan for the Noble EYE sensor. The RFI invited contractor agencies to furnish thoughts on their capabilities and to assess the state-of-the-art in technologies relevant to the successful development of the Noble EYE sensor. Ethics/conflict-of-interest rules forbade our participation in the active review of contractor replies to the RFI.

We supported efforts to advance the possibility of co-manifesting the Noble EYE sensor with either the expected NASA Landsat Data Continuity Mission (LDCM) satellite or a separate satellite involving international cooperation. The Noble EYE sensor would provide hyperspectral data from a space-based platform. The partnering studies involved: (1) LDCM effort – teaming with Resource21, Boeing, and other corporations through an AFRL CRADA, and (2) separate effort – teaming with an international group to determine the technical feasibility of either co-manifesting Noble EYE with a second sensor to meet the partners' needs ***or*** constructing and flying a single sensor that would combine the needs of both groups.

2.4 Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH)

The HIE-06 program was a High Power Computing effort to convert the FLAASH atmospheric compensation code from an IDL single-string code to a C++ code running in a highly parallel architecture. FLAASH was ported from IDL to C by Spectral Sciences, Inc., and the C version was adapted for use on supercomputers, including highly-parallel Beowulf clusters, which consist of dozens of moderate-capability PCs that are linked together to form a super-computer. We participated in the Alpha Test process for the parallelization effort. This work included testing the Alpha-level software, reporting bugs/deficiencies, monitoring responsiveness to such reports including resolution of the flaws, and reviewing code, documentation, and program management elements. The official Alpha test was successfully performed for the HIE project management on 4 June 2002. We continued to be involved in this effort as Beta-testers and were also involved in efforts to add improvements to the FLAASH science code.

Hyperspectral data for real-world scenes must contend with the effects of shade from buildings, trees, clouds, and terrain issues. For example, viewing down onto a mountain one observes a fully sunlit side, followed by regions of partial shade from trees, outcroppings, and relief, ending with a region that is completely shaded by the bulk of the mountain. Because the illumination source varies greatly between these regions (from full direct Sun plus skyshine all the way to solely skyshine), matching items (e.g., oak trees) from each region would have dramatically different recorded radiance spectra. Hyperspectral sensors record the radiance that reaches them, but atmospheric correction packages, such as FLAASH, assume that all pixels have the same source light, which is direct sunshine plus a meteorological-dependent term for scattered skyshine. To accurately assess the intrinsic reflectance of a scene pixel, a shade detection algorithm and correction factors were developed that, when properly implemented, would change the reported radiance spectrum for a shaded pixel into the corrected radiance value that would have been observed if the full sunlight had illuminated the material in the scene. This would enable the analysis of the pixel to provide the correct surface reflectance.

We supported an effort that would greatly evolve the FLAASH atmospheric compensation code. Several aspects of this code have been under development and are now being written into the code. This includes modules for shadow detection and spectral correction, identification and compensation for spectral "smile" (where a two-dimensional detector does not have a single set of assignable wavelengths for the entire data set), correction factors that pertain to data acquired off-nadir, i.e., on a slant path through the atmosphere, and several other components. We participated in efforts to define and solve the shadow and spectral smile problems, and those efforts are now being expanded to be included in the FLAASH code. We also calculated sensitivity parameters to describe the grid factors that are necessary and sufficient to describe the multi-dimensional solution space for atmospheric compensation. For example, gridding that is sufficient for high altitude sensors (e.g., 20 km overflights) do not adequately compensate the atmospheric effects on low, variable altitude platforms (e.g., an aircraft that varies its altitude from 2 to 8 km).

2.5 Scene Simulation Code Effort

An additional effort was participation in a team effort (with AFRL, Stewart Radiance Lab, and Mission Research Corp. personnel) to test computer codes that would create simulations of scenes for a given sensor and set of scene input parameters. One such code is "SST/HSI" provided to AFRL by PRA, Inc. (a separate contractor). Briefly, their code combines several modules from various sources that calculate atmospheric and illumination effects on items in a given scene, including MODTRAN, DIRSIG, HYSIM, and other modules. Although these modules are intended to be merged, some of them (most notably DIRSIG) are incomplete and functioning versions have not been fully delivered by either PRA or the individual component authors. In addition, the SST/HSI wrapper did not actually enable all the modules to work together, for example, a serious problem is a mismatch in east-west longitude inputs. During the October – December 2002 timeframe, we participated heavily in the development of guidelines for both the overall approach to modeling such scenes and specific recommendations for the evolution of the SST/HSI testbed into a functional software package. Our inputs were merged with those of other contractors for inclusion in two "Interface Control"-style documents.

2.6 COMPASS Hyperspectral Program

Other efforts included work to verify and validate the COMPASS sensor calibration effort. We participated in a site visit to the COMPASS group offices to discuss collaboration points and establish procedures for instrument calibration. We have also participated in on-going efforts to guide a ground-truth experiment where painted panels are placed at known locations to provide a standard set of scene image components for aircraft- and space-based hyperspectral systems. The panels are located at a "Warfighter-1 calibration site" that now serves as a calibration site for the COMPASS and intended Noble EYE programs. The COMPASS group required a significant amount of guidance to provide minimally useful calibration data. We participated in efforts to determine an instrument calibration from such data sets, and we identified a number of deficiencies in the COMPASS laboratory data collection. For example, the read-out electronics could be set to run as slowly as 12 Hz, with 250 Hz being the standard rate for field data collection. In 12 Hz mode, a clocking cycle became mis-timed and an entire spectral column was being lost by the system. The COMPASS group was not able to determine which column of data was being lost, but our analysis identified the missing column and established that the 12 Hz rate could not be used in field data collection efforts.

3. SUMMARY

To summarize, we performed hyperspectral data analysis required to advance the Air Force interests in the use of this technology. Our efforts also advanced the state-of-the-art in atmospheric compensation codes.